# Extreme Kuiper Belt Object 2001 $QG_{298}$ and the Fraction of Contact Binaries

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## ABSTRACT

Extensive time-resolved observations of Kuiper Belt object 2001 $QG_{298}$ show a lightcurve with a peak-to-peak variation of $1.14 \pm 0.04$ magnitudes and single-peaked period of $6.8872 \pm 0.0002$ hr. The mean absolute magnitude is 6.85 magnitudes which corresponds to a mean effective radius of 122 (77) km if an albedo of 0.04 (0.10) is assumed. This is the first known Kuiper Belt object and only the third minor planet with a radius $> 25$ km to display a lightcurve with a range in excess of 1 magnitude. We find the colors to be typical for a Kuiper Belt object ($B - V = 1.00 \pm 0.04$, $V - R = 0.60 \pm 0.02$) with no variation in color between minimum and maximum light. The large light variation, relatively long double-peaked period and absence of rotational color change argue against explanations due to albedo markings or elongation due to high angular momentum. Instead, we suggest that 2001 $QG_{298}$ may be a very close or contact binary similar in structure to what has been independently proposed for the Trojan asteroid 624 Hektor. If so, its rotational period would be twice the lightcurve period or $13.7744 \pm 0.0004$ hr. By correcting for the effects of projection, we estimate that the fraction of similar objects in the Kuiper Belt is at least $\sim$10% to 20% with the true fraction probably much higher. A high abundance of close and contact binaries is expected in some scenarios for the evolution of binary Kuiper Belt objects.

*Subject headings:* Kuiper Belt, Oort Cloud - minor planets, solar system: general

## 1. Introduction

The Kuiper Belt is a long-lived region of the Solar System just beyond Neptune where the planetisimals have not coalesced into a planet. It contains about 80,000 objects with radii greater than 50 km (Trujillo, Jewitt & Luu 2001) which have been collisionally processed and gravitationally perturbed throughout the age of the Solar System. The short-period comets and

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Centaurs are believed to originate from the Kuiper Belt (Fernandez 1980; Duncan, Quinn & Tremaine 1988).

Physically, the Kuiper Belt objects (KBOs) show a large diversity of colors from slightly blue to ultra red ($V-R \sim 0.3$ to $V-R \sim 0.8$, Luu and Jewitt 1996) and may show correlations between colors, inclination and/or perihelion distance (Jewitt & Luu 2001; Trujillo & Brown 2002; Doressoundiram et al. 2002; Tegler & Romanishin 2003). Spectra of KBOs are mostly featureless with a few showing hints of water ice (Brown, Cruikshank & Pendleton 1999; Jewitt & Luu 2001; Lazzarin et al. 2003). The range of KBO geometric albedos is still poorly sampled but the larger ones likely have values between 0.04 to 0.10 (Jewitt, Aussel & Evans 2001; Altenhoff, Bertoldi & Menten 2004). Time-resolved observations of KBOs show that $\sim 32\%$ vary by $\geq 0.15$ magnitudes, 18% by $\geq 0.40$ magnitudes and 12% by $\geq 0.60$ magnitudes (Sheppard & Jewitt 2002; Ortiz et al. 2003; Lacerda & Luu 2003; Sheppard & Jewitt 2004). One object, (20000) Varuna, displays a large photometric range and fast rotation which is best interpreted as a structurally weak object elongated by its own rotational angular momentum (Jewitt & Sheppard 2002). A significant fraction of KBOs appear to be more elongated than main-belt asteroids of similar size (Sheppard & Jewitt 2002). The KBO phase functions are steep, with a median of 0.16 magnitudes per degree between phase angles of 0 and 2 degrees (Sheppard & Jewitt 2002; Schaefer & Rabinowitz 2002; Sheppard & Jewitt 2004).

About $4\% \pm 2\%$ of the KBOs are binaries with separations $\geq 0.15''$ (Noll et al. 2002) while binaries with separations $\geq 0.1''$ may constitute about 15% of the population (Trujillo 2003, private communication). All the binary KBOs found to date appear to have mass ratios near unity, though this may be an observational selection effect. The mechanism responsible for creating KBO binaries is not clear. Formation through collisions is unlikely (Stern 2002). Weidenschilling (2002) has proposed formation of such binaries through complex three-body interactions which would only occur efficiently in a much higher population of large KBOs than can currently be accounted for. Goldreich, Lithwick & Sari (2002) have proposed that KBO binaries could have formed when two bodies approach each other and energy is extracted either by dynamical friction from the surrounding sea of smaller KBOs or by a close third body. This process also requires that the density of KBOs was $\sim 10^2$ to $10^3$ times greater than now. They predict that closer binaries should be more abundant in the Kuiper Belt while Weidenschilling's mechanism predicts the opposite.

The present paper is the fourth in a series resulting from the Hawaii Kuiper Belt variability project (HKBVP, see Jewitt & Sheppard 2002; Sheppard & Jewitt 2002; Sheppard & Jewitt 2004). The practical aim of the project is to determine the rotational characteristics (principally period and shape) of bright KBOs ($m_R \leq 22$) in order to learn about the distributions of rotation period and shape in these objects. In the course of this survey we found that 2001 $QG_{298}$ had an extremely large light variation and a relatively long period. We have obtained optical observations of 2001 $QG_{298}$ in order to accurately determine the rotational lightcurve and constrain its possible causes. 2001 $QG_{298}$ has a typical Plutino orbit in 3:2 mean-motion resonance with Neptune,

semi-major axis at 39.2 AU, eccentricity of 0.19 and inclination of 6.5 degrees.

## 2. Observations

We used the University of Hawaii (UH) 2.2 m diameter telescope atop Mauna Kea in Hawaii to obtain R-band observations of 2001 $QG_{298}$ on three separate observing runs each covering several nights: UT September 12 and 13 2002; August 22, 26, 27 and 28 2003; September 27, 28 and 30 2003. Two different CCD cameras were employed. For the September 2002 and September 2003 observations we used a $2048 \times 2048$ pixel Tektronix CCD (24 $\mu$m pixels) camera with a $0.''219$ pixel$^{-1}$ scale at the f/10 Cassegrain focus. An antireflection coating on the CCD gave very high average quantum efficiency (0.90) in the R-band. The field-of-view was $7'.5 \times 7'.5$. For the August 2003 observations we used the Orthogonal Parallel Transfer Imaging Camera (OPTIC). OPTIC has two $4104 \times 2048$ pixel Lincoln Lab CCID28 Orthogonal Transfer CCDs developed to compensate for real-time image motion by moving the charge on the chips to compensate for seeing variations (Tonry, Burke & Schechter 1997). Howell et al. (2003) have demonstrated that these chips are photometrically accurate and provide routine sharpening of the image point spread function. There is a $\sim 15''$ gap between the chips. The total field-of-view was $9'.5 \times 9'.5$ with 15 $\mu$m pixels which corresponds to $0.14''$ pixel$^{-1}$ scale at the f/10 Cassegrain focus. The same R-band filter based on the Johnson-Kron-Cousins photometric system was used for all UH 2.2 m observations.

In addition we used the Keck I 10 m telescope to obtain BVR colors of 2001 QG298 at its maximum and minimum light on UT August 30, 2003. The LRIS camera with its Tektronix $2048 \times 2048$ pixel CCD and 24 $\mu$m pixels (image scale $0.''215$ pixel$^{-1}$) was used (Oke et al. 1995) with the facility broadband BVR filter set. Due to a technical problem with the blue camera side we used only the red side for photometry at BV and R. The blue filter response was cut by the use of a dichroic at 0.460 $\mu$m.

All exposures were taken in a consistent manner with the telescope autoguided on bright nearby stars. The seeing ranged from $0.''6$ to $1.0''$ during the various observations. 2001 $QG_{298}$ moved relative to the fixed stars at a maximum of $3''.5$ hr$^{-1}$ corresponding to trail lengths $\leq 0.''43$ in the longest (450 sec) exposures. Thus motion of the object was insignificant compared to the seeing.

Images from the UH telescope were bias-subtracted and then flat-fielded using the median of a set of dithered images of the twilight sky. Data from Keck were bias subtracted and flattened using flat fields obtained from an illuminated spot inside the closed dome. Landolt (1992) standard stars were employed for the absolute photometric calibration. To optimize the signal-to-noise ratio we performed aperture correction photometry by using a small aperture on 2001 $QG_{298}$ ($0.''65$ to $0.''88$ in radius) and both the same small aperture and a large aperture ($2.''40$ to $3.''29$ in radius) on (four or more) nearby bright field stars. We corrected the magnitude within the small aperture

used for the KBOs by determining the correction from the small to the large aperture using the field stars (c.f. Tegler and Romanishin 2000; Jewitt & Luu 2001; Sheppard & Jewitt 2002). Since 2001 $QG_{298}$ moved slowly we were able to use the same field stars from night to night within each observing run, resulting in very stable relative photometric calibration from night to night. The observational geometry for 2001 $QG_{298}$ on each night of observation is shown in Table 1.

## 3. Results

Tables 2 and 3 show the photometric results for 2001 $QG_{298}$. We used the phase dispersion minimization (PDM) method (Stellingwerf 1978) to search for periodicity in the data. In PDM, the metric is the so-called $\Theta$ parameter, which is essentially the variance of the unphased data divided by the variance of the data when phased by a given period. The best-fit period should have a very small dispersion compared to the unphased data and thus $\Theta << 1$ indicates that a good fit has been found.

2001 $QG_{298}$ showed substantial variability ($\sim 1.1$ magnitudes with a single-peaked period near 6.9 hr) in R-band observations from two nights in September 2002. We obtained further observations of the object in 2003 to determine the lightcurve with greater accuracy. PDM analysis of all the apparent magnitude R-band data from the September 2002 and August and September 2003 observations shows that 2001 $QG_{298}$ has strong $\Theta$ minima near the periods $P = 6.88$ hr and $P = 13.77$ hr, with weaker alias periods flanking these (Figure 1). We corrected the apparent magnitude data for the minor phase angle effects (we used the nominal 0.16 magnitudes per degree found in Sheppard & Jewitt 2003) and light travel-time differences of the observations to correspond to the August 30, 2003 observations. We then phased the data to all the peaks with $\Theta < 0.4$ and found only the 6.8872 and 13.7744 hour periods to be consistent with all the data (Figures 2 and 3). Through a closer look at the PDM plot (Figure 4) and phasing the data we find best fit periods $P = 6.8872 \pm 0.0002$ hr (a lightcurve with a single maximum per period) and $P = 13.7744 \pm 0.0004$ hr (two maxima per period as expected for rotational modulation caused by an aspherical shape). The double-peaked lightcurve appears to be the best fit with the minima different by about 0.1 magnitudes while the maxima appear to be of similar brightness. The photometric range of the lightcurve is $\Delta m = 1.14 \pm 0.04$ magnitudes.

The Keck BVR colors of 2001 $QG_{298}$ show no variation from minimum to maximum light within the photometric uncertainties of a few % (see Figures 2 and 3). This is again consistent with a lightcurve that is produced by an elongated shape, rather than by albedo variations. The colors ($B - V = 1.00 \pm 0.04$, $V - R = 0.60 \pm 0.02$) show that 2001 $QG_{298}$ is red and similar to the mean values ($B - V = 0.98 \pm 0.04$, $V - R = 0.61 \pm 0.02$, 28 objects) for KBOs as a group (Jewitt and Luu 2001).

The absolute magnitude of a Solar System object, $m_R(1, 1, 0)$, is the hypothetical magnitude the object would have if it where at heliocentric ($R$) and geocentric ($\Delta$) distances of 1 AU and

had a phase angle ($\alpha$) of 0 degrees. We use the relation $m_R(1,1,0) = m_R - 5\log(R\Delta) - \beta\alpha$ to find the absolute magnitude by correcting for the geometrical and phase angle effects in the 2001 $QG_{298}$ observations. Here $m_R$ is the apparent red magnitude of the object and $\beta$ is the phase function. Using the nominal value of $\beta = 0.16$ magnitudes per degree for KBOs at low phase angles (Sheppard & Jewitt 2002; Sheppard & Jewitt 2004) and data from Table 1 we find that 2001 $QG_{298}$ has $m_R(1,1,0) = 6.28 \pm 0.02$ at maximum light and $m_R(1,1,0) = 7.42 \pm 0.02$ magnitudes at minimum light. If attributed to a rotational variation of the cross-section, this corresponds to a ratio of maximum to minimum areas of 2.85:1.

The effective radius of an object can be calculated using the relation $m_R(1,1,0) = m_\odot - 2.5\log\left[p_R r_e^2/2.25 \times 10^{16}\right]$ where $m_\odot$ is the apparent red magnitude of the sun ($-27.1$), $p_R$ is the red geometric albedo and $r_e$ (km) is the effective circular radius of the object. If we assume an albedo of 0.04 (0.10) this corresponds to effective circular radii at maximum and minimum light of about 158 (100) km and 94 (59) km, respectively. At the mean absolute magnitude of 6.85 mag, the effective circular radius is 122 (77) km.

## 4. Analysis

Only three other objects in the Solar System larger than 25 km in radius are known to have lightcurve ranges $> 1.0$ magnitude (Table 4). Following Jewitt and Sheppard (2002) we discuss three possible models of rotational variation to try to compare the objects from Table 4 with 2001 $QG_{298}$.

### 4.1. Albedo Variation

On asteroids, albedo variations contribute brightness variations that are usually less than about $10\% - 20\%$ (Degewij, Tedesco & Zellner 1979). Rotationally correlated color variations may be seen if the albedo variations are large since materials with markedly different albedos may differ compositionally. As seen in Table 4, Saturn's satellite Iapetus is the only object in which variations $\geq$1 mag. are explained through albedo. The large albedo contrast on Iapetus is likely a special consequence of its synchronous rotation and the anisotropic impact of material trapped in orbit about Saturn onto its leading hemisphere (Cook & Franklin 1970). Iapetus shows clear rotational color variations ($\Delta(B-V) \sim 0.1$ mag.) that are correlated with the rotational albedo variations (Millis 1977) and which would be detected in 2001 $QG_{298}$ given the quality of our data. The special circumstance of Iapetus is without obvious analogy in the Kuiper Belt and we do not believe that it is a good model for the extreme lightcurve of 2001 $QG_{298}$.

Pluto shows a much smaller variation (about 0.3 magnitudes) thought to be caused by albedo structure (Buie, Tholen & Wasserman 1997). Pluto is so large that it can sustain an atmosphere which may contribute to amplifying its lightcurve range by allowing surface frosts to condense on

brighter (cooler) spots. Thus brighter spots grow brighter while darker (hotter) spots grow darker through the sublimation of ices. This positive feedback mechanism requires an atmosphere and is unlikely to be relevant on a KBO as small as 2001 $QG_{298}$.

While we cannot absolutely exclude surface markings as the dominant cause of 2001 $QG_{298}$'s large rotational brightness variation, we are highly skeptical of this explanation. We measure no color variation with rotation, there appear to be two distinct minima and the range is so large as to be beyond reasonable explanation from albedo alone.

### 4.2. Aspherical Shape

Since surface markings are most likely not the cause of the lightcurve, the observed photometric variations are probably caused by changes in the projected cross-section of an elongated body in rotation about its minor axis. The rotation period of an elongated object should be twice the single-peaked lightcurve period because of the projection of both long axes (2 maxima) and short axes (2 minima) during one full rotation. If the body is elongated, we can use the ratio of maximum to minimum brightness to determine the projection of the body shape into the plane of the sky. The rotational brightness range of a triaxial object with semiaxes $a \geq b \geq c$ in rotation about the $c$ axis and viewed equatorially is

$$\Delta m = 2.5 \log \left( \frac{a}{b} \right) \tag{1}$$

where $\Delta m$ is expressed in magnitudes. This gives a lower limit to $a/b$ because of the effects of projection. Using $\Delta m = 1.14$ for 2001 $QG_{298}$, we find the lower limit is $a/b = 2.85$. This corresponds to $a = 267$ and $b = 94$ km for the geometric albedo 0.04 case and $a = 169$ and $b = 59$ km for an albedo of 0.10.

It is possible that 2001 $QG_{298}$ is elongated and able to resist gravitational compression into a spherical shape by virtue of its intrinsic compressive strength. However, observations of asteroids in the main-belt suggest that only the smallest ($\sim$0.1 km sized) asteroids are in possession of a tensile strength sufficient to resist rotational deformation (Pravec, Harris & Michalowski 2003). Observations of both asteroids and planetary satellites suggest that many objects with radii $\geq 50$ to 75 km have shapes controlled by self-gravity, not by material strength (Farinella 1987; Farinella & Zappala 1997). The widely accepted explanation is that these bodies are internally weak because they have been fractured by numerous past impacts. This explanation is also plausible in the Kuiper Belt, where models attest to a harsh collisional environment at early times (e.g. Davis & Farinella 1997). We feel that the extraordinarily large amplitude of 2001 $QG_{298}$ is unlikely to be caused by elongation of the object sustained by its own material strength, although we cannot rule out this possibility.

Structurally weak bodies are susceptible to rotational deformation. The 1000-km scale KBO

(20000) Varuna (rotation period 6.3442 ± 0.0002 hr and lightcurve range 0.42 ± 0.02 mag) is the best current example in the Kuiper Belt (Jewitt and Sheppard 2002). In the main asteroid belt, 216 Kleopatra has a very short period (5.385 hr) and large lightcurve range (1.18 mag., corresponding to axis ratio ∼2.95:1 and dimensions ∼ 217 × 94 km, Table 4). Kleopatra has been observed to be a highly elongated body through radar and high resolution imaging and the most likely explanation is that 216 Kleopatra is rotationally deformed (Leone et al. 1984; Ostro et al. 2000; Hestroffer et al. 2002; Washabaugh & Scheeres 2002). Is rotational elongation a viable model for 2001 $QG_{298}$?

The critical rotation period ($T_{crit}$) at which centripetal acceleration equals gravitational acceleration towards the center of a rotating spherical object is

$$T_{crit} = \left(\frac{3\pi}{G\rho}\right)^{1/2} \tag{2}$$

where $G$ is the gravitational constant and $\rho$ is the density of the object. With $\rho = 1000$ kg $m^{-3}$ the critical period is about 3.3 hr. Even at longer periods, real bodies will suffer centripetal deformation into triaxial aspherical shapes which depend on their density, angular momentum and material strength. The limiting equilibrium shapes of rotating strengthless fluid bodies have been well studied by Chandrasekhar (1987) and a detailed discussion in the context of the KBOs can be found in Jewitt and Sheppard (2002). We briefly mention here that triaxial "Jacobi" ellipsoids with large angular momenta are rotationally elongated and generate lightcurves with substantial ranges when viewed equatorially.

Leone et al. (1984) have analyzed rotational equilibrium configurations of strengthless asteroids in detail (see Figure 5). They show that the maximum photometric range of a rotational ellipsoid is 0.9 mag: more elongated objects are unstable to rotational fission. The 1.14 mag photometric range of 2001 $QG_{298}$ exceeds this limit. In addition, the 13.7744 hr (two-peaked) rotation period is much too long to cause significant elongation for any plausible bulk density (Figure 5). For these reasons we do not believe that 2001 $QG_{298}$ is a single rotationally distorted object.

### 4.3. Binary Configurations

A third possible explanation for the extreme lightcurve of 2001 $QG_{298}$ is that this is an eclipsing binary. A wide separation (sum of the orbital semi-major axes much larger than the sum of the component radii) is unlikely because such a system would generate a distinctive "notched" lightcurve that is unlike the lightcurve of 2001 $QG_{298}$. In addition, a wide separation would require unreasonably high bulk density of the components in order to generate the measured rotational period. If 2001 $QG_{298}$ is a binary then the components must be close or in contact. We next consider the limiting case of a contact binary.

The axis ratio of a contact binary consisting of equal spheres is $a/b = 2$, corresponding to a lightcurve range $\Delta m = 0.75$ magnitudes, as seen from the rotational equator. At the average viewing angle $\theta = 60$ degrees we would expect $\Delta m = 0.45$ mag. The rotational variation of 2001 $QG_{298}$ is too large to be explained as a contact binary consisting of two equal spheres. However, close binary components of low strength should be elongated by mutual tidal forces, giving a larger lightcurve range than possible in the case of equal spheres (Leone et al. 1984). The latter authors find that the maximum range for a tidally distorted nearly contact binary is 1.2 magnitudes, compatible with the 1.14 mag. range of 2001 $QG_{298}$ (Figure 5). The contact binary hypothesis is the likely explanation of 624 Hektor's lightcurve (Hartmann & Cruikshank 1978; Weidenschilling 1980; Leone et al. 1984) and could also explain 216 Kleopatra's lightcurve (Leone et al. 1984; Ostro et al. 2000; Hestroffer et al. 2002).

We suggest that the relatively long double-peaked period ($13.7744 \pm 0.0004$ hr) and large photometric range ($1.14 \pm 0.04$ magnitudes) of 2001 $QG_{298}$'s lightcurve are best understood if the body is a contact binary or nearly contact binary viewed from an approximately equatorial perspective. The large range suggests that the components are of similar size and are distorted by their mutual tidal interactions. Using the calculations from Leone et al. (1984), who take into account the mutual deformation of close, strengthless binary components, we find the density of these objects must be $\sim$1000 kg m$^{-3}$ in order to remain bound in a binary system separated by the Roche radius (which is just over twice the component radius). If we assume that the albedo of both objects is 0.04, the effective radius of each component is about 95 km as found above. Using this information we find from Kepler's third law that if the components are separated, they would be about 300 km apart. This separation as seen on the sky ($0.01''$) is small enough to have escaped resolution with current technology.

Further, we point out that the maximum of the lightcurve of 2001 $QG_{298}$ is more nearly "U" shaped (or flattened) than is the "V" shaped minimum (Figure 3). This is also true for 624 Hektor (Dunlap & Gehrels 1969) and may be a distinguishing, though not unique, signature of a contact or nearly contact binary (Zappala 1984; Leone et al. 1984; Cellino et al. 1985). In comparison, (20000) Varuna, which is probably not a contact binary (see below and Jewitt & Sheppard 2002), does not show significant differences in the curvature of the lightcurve maxima and minima.

In short, while we cannot prove that 2001 $QG_{298}$ is a contact binary, we find by elimination of other possibilities that this is the most convincing explanation of its lightcurve.

### 4.4. Fraction of Contact Binaries in the Kuiper Belt

The distribution of measured lightcurve properties is shown in Figure 5 (adapted from Figure 4 of Leone et al. (1984)). There, Region A corresponds to the low rotational range objects (of any period) in which the variability can be plausibly associated with surface albedo markings. Region B corresponds to the rotationally deformed Jacobi ellipsoids while Region

C marks the domain of the close binary objects. Plotted in the Figure are the lightcurve periods and ranges for KBOs from the HKBVP (Jewitt & Sheppard 2002; Sheppard & Jewitt 2002; Sheppard & Jewitt 2004). We also show large main belt asteroids (data from http://cfa-www.harvard.edu/iau/lists/LightcurveDat.html updated by A. Harris and B. Warner and based on Lagerkvist, Harris & Zappala 1989). Once again we note that the measured KBO ranges should, in most cases, be regarded as lower limits to the range because of the possible effects of projection into the plane of the sky.

Of the 34 KBOs in our sample, five fall into Region C in Figure 5. Of these, 2001 $QG_{298}$ is by far the best candidate for being a contact or nearly contact binary system since it alone has a range between the $\Delta m_R \sim 0.9$ mag. limit for a single rotational equilibrium ellipsoid and the $\Delta m_R \sim$1.2 mag. limit for a mutually distorted close binary (Table 5). It is also rotating too slowly to be substantially distorted by its own spin (Figure 5). Both (33128) 1998 $BU_{48}$ and 2000 $GN_{171}$ are good candidates which have large photometric ranges and relatively slow periods. KBOs (26308) 1998 $SM_{165}$ and (32929) 1995 $QY_9$ could be rotationally deformed ellipsoids, but their relatively slow rotations would require densities much smaller than that of water, a prospect which we consider unlikely.

We next ask what might be the abundance of contact or close binaries in the Kuiper Belt. As a first estimate we assume that we have detected one such object (2001 $QG_{298}$) in a sample of 34 KBOs observed with adequate time resolution. The answer depends on the magnitude of the correction for projection effects caused by the orientation of the rotation vector with respect to the line of sight. This correction is intrinsically uncertain, since it depends on unknowns such as the scattering function of the surface materials of the KBO as well as on the detailed shape. We adopt two crude approximations that should give the projection correction at least to within a factor of a few.

First, we represent the elongated shape of the KBO by a rectangular block with dimensions a $>$ b = c. The lightcurve range varies with angle from the equator, $\theta$, in this approximation as

$$\Delta m = 2.5 log \left[ \frac{1 + tan\theta}{\frac{b}{a} + tan\theta} \right]. \quad (3)$$

For the limiting case of a highly distorted contact binary with $\Delta m = 1.2$ mag. at $\theta = 0°$, Eq. (3) gives $a/b = 3$. We next assume that the range must fall in the range $0.9 \leq \Delta m \leq 1.2$ mag. in order for us to make an assignment of likely binary structure (Figure 6). As noted above, only 2001 $QG_{298}$ satisfies this condition amongst the known objects. We find, from Eq. (3) with $a/b = 3$, that $\Delta m = 0.9$ mag is reached at $\theta = 10°$. The probability that Earth would lie within 10° of the equator of a set of randomly oriented KBOs is $P(\theta \leq 10) = 0.17$. Therefore, the detection of 1 KBO with $0.9 \leq \Delta m \leq 1.2$ mag implies that the fractional abundance of similarly elongated objects is $f \sim 1/(34P) \sim 17\%$.

As a separate check on this estimate, we next represent the object as an ellipsoid, again with

axes a > b = c. The photometric range when viewed at an angle $\theta$ from the rotational equator is given by

$$\Delta m = 2.5log(a/b) - 1.25log\left[\left[\left(\frac{a}{b}\right)^2 - 1\right] sin^2\theta + 1\right] \quad (4)$$

Substituting $a/b = 3$, the range predicted by Eq. (4) falls to 0.9 mag at $\theta \sim 17°$. Given a random distribution of the spin vectors, the probability that Earth would lie within 17° of the equator is $P(\theta \leq 17) = 0.29$. Therefore, the detection of 1 KBO with a range between 0.9 and 1.2 mag in a sample of 34 objects implies, in this approximation, a fractional abundance of similarly elongated objects near $f \sim 1/(34P) \sim 10\%$.

Given the crudity of the model, the agreement between projection factors from Eqs. (3) and (4) is encouraging. Together, the data and the projection factors suggest that in our sample of 34 KBOs, perhaps 3 to 6 objects are as elongated as 2001 $QG_{298}$ but only 2001 $QG_{298}$ is viewed from a sufficiently equatorial perspective that the lightcurve is distinct. This is consistent with Figure 5, which shows that 5 of 34 KBOs (15%) from the HKBVP occupy Region C of the period-range diagram. Our estimate is very crude and is also a lower limit to the true binary fraction because close binaries with components of unequal size will not satisfy the $0.9 \leq \Delta m \leq 1.2$ mag. criterion for detection. The key point is that the data are consistent with a substantial close binary fraction in the Kuiper Belt .

Figure 5 also shows that there are no large main-belt asteroids (radii $\geq$ 100 km) in Region C, which is where similar sized component contact binaries are expected to be. To date, no examples of large binary main-belt asteroids with similar sized components have been found, even though the main belt has been extensively searched for binarity (see Margot 2002 and references therein). The main-belt asteroids may have had a collisional history significantly different from that of the KBOs.

The contact binary interpretation of the 2001 $QG_{298}$ lightcurve is clearly non-unique. Indeed, firm proof of the existence of contact binaries will be as difficult to establish in the Kuiper Belt as it has been in closer, brighter populations of small bodies. Nevertheless, the data are compatible with a high abundance of such objects. It is interesting to speculate about how such objects could form in abundance. One model of the formation and long term evolution of wide binaries predicts that such objects could be driven together by dynamical friction or three-body interactions (Goldreich et al. 2002). Objects like 2001 $QG_{298}$ would be naturally produced by such a mechanism.

## 5. Summary

Kuiper Belt Object 2001 $QG_{298}$ has the most extreme lightcurve of any of the 34 objects so far observed in the Hawaii Kuiper Belt Variability Project.

1. The double-peaked lightcurve period is $13.7744 \pm 0.0004$ hr and peak-to-peak range is $1.14 \pm 0.04$ mag. Only two other minor planets with radii $\geq 25$ km (624 Hektor and 216 Kleopatra) and one planetary satellite (Iapetus) are known to show rotational photometric variation greater than 1 mag.

2. The absolute red magnitude is $m_R(1,1,0) = 6.28$ at maximum light and 7.42 mag. at minimum light. With an assumed geometric albedo of 0.04 (0.10) we derive effective circular radii at maximum and minimum light of 158 (100) and 94 (59) km, respectively.

3. No variation in the BVR colors between maximum and minimum light was detected to within photometric uncertainties of a few percent.

4. The large photometric range, differences in the lightcurve minima, and long period of 2001 $QG_{298}$ are consistent with and strongly suggest that this object is a contact or nearly contact binary, viewed equatorially.

5. If 2001 $QG_{298}$ is a contact binary with similarly sized components, then we conclude that such objects constitute at least 10% to 20% of the Kuiper Belt population at large sizes.

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Fig. 1.— The phase dispersion minimization (PDM) plot for 2001 $QG_{298}$. A smaller theta corresponds to a better fit. Best fits from this plot are the 6.8872 hour single-peaked fit and the 13.7744 hour double-peaked fit. Both are flanked by alias periods.

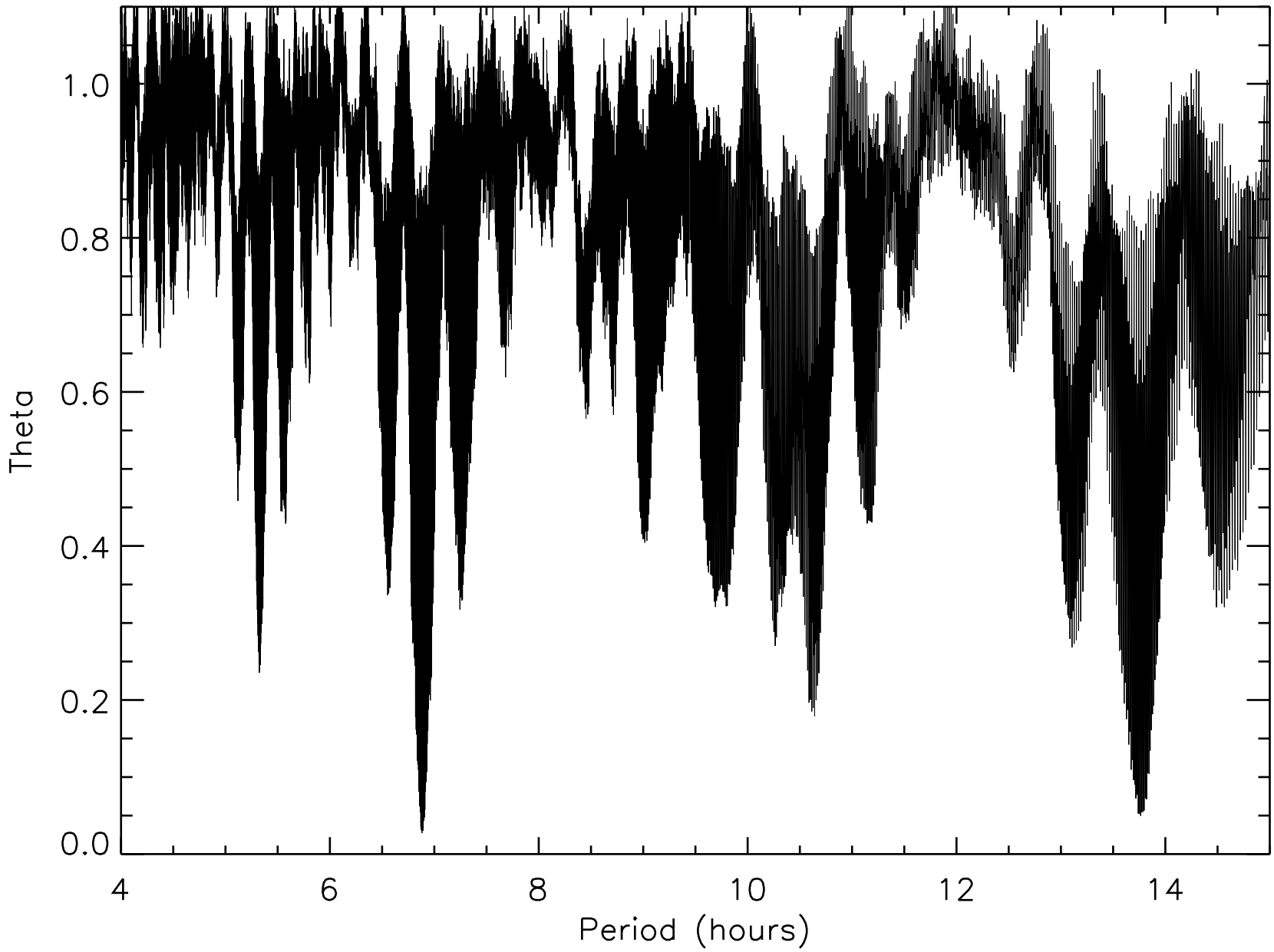
Fig. 2.— Phased data from all the observations in 2002 and 2003 of 2001 $QG_{298}$. The period has been phased to 6.8872 hr which is the best fit single-peaked period. Filled colored symbols are data taken in the B-band (blue), V-band (green) and R-band (red) at the Keck I telescope on UT August 30. All other symbols are R-band data from the various nights of observations at UH 2.2 m telescope. The $B$ and $V$ points have been shifted according to their color differences from the R-band ($V - R = 0.60$ and $B - V = 1.00$). No color variation is seen between maximum and minimum light. The uncertainty on each photometric observation is $\pm 0.03$ mag.

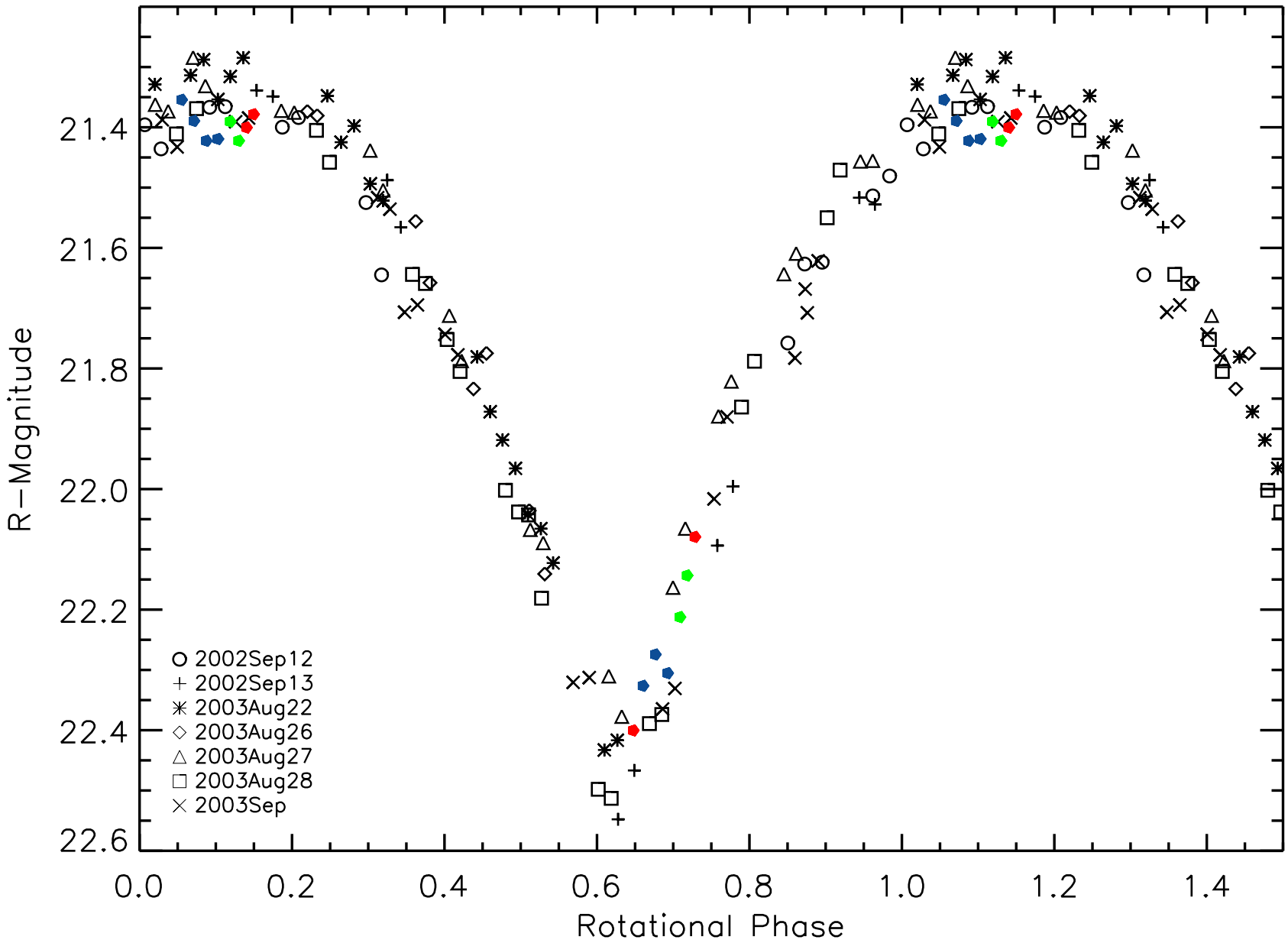
Fig. 3.— Phased data from all the observations in 2002 and 2003 of 2001 $QG_{298}$. The period has been phased to 13.7744 hr which is the best fit double-peaked period. Filled colored symbols are data taken in the B-band (blue), V-band (green) and R-band (red) at the Keck I telescope on UT August 30. All other symbols are R-band data from the various nights of observations at UH 2.2 m telescope. The $B$ and $V$ points have been shifted according to their color differences from the R-band ($V - R = 0.60$ and $B - V = 1.00$). There appears to be two distinct minima. The minima appear to be more "notched" compared to the flatter maxima. No color variation is seen between maximum and minimum light. The uncertainty for each photometric observation is $\pm 0.03$ mag.

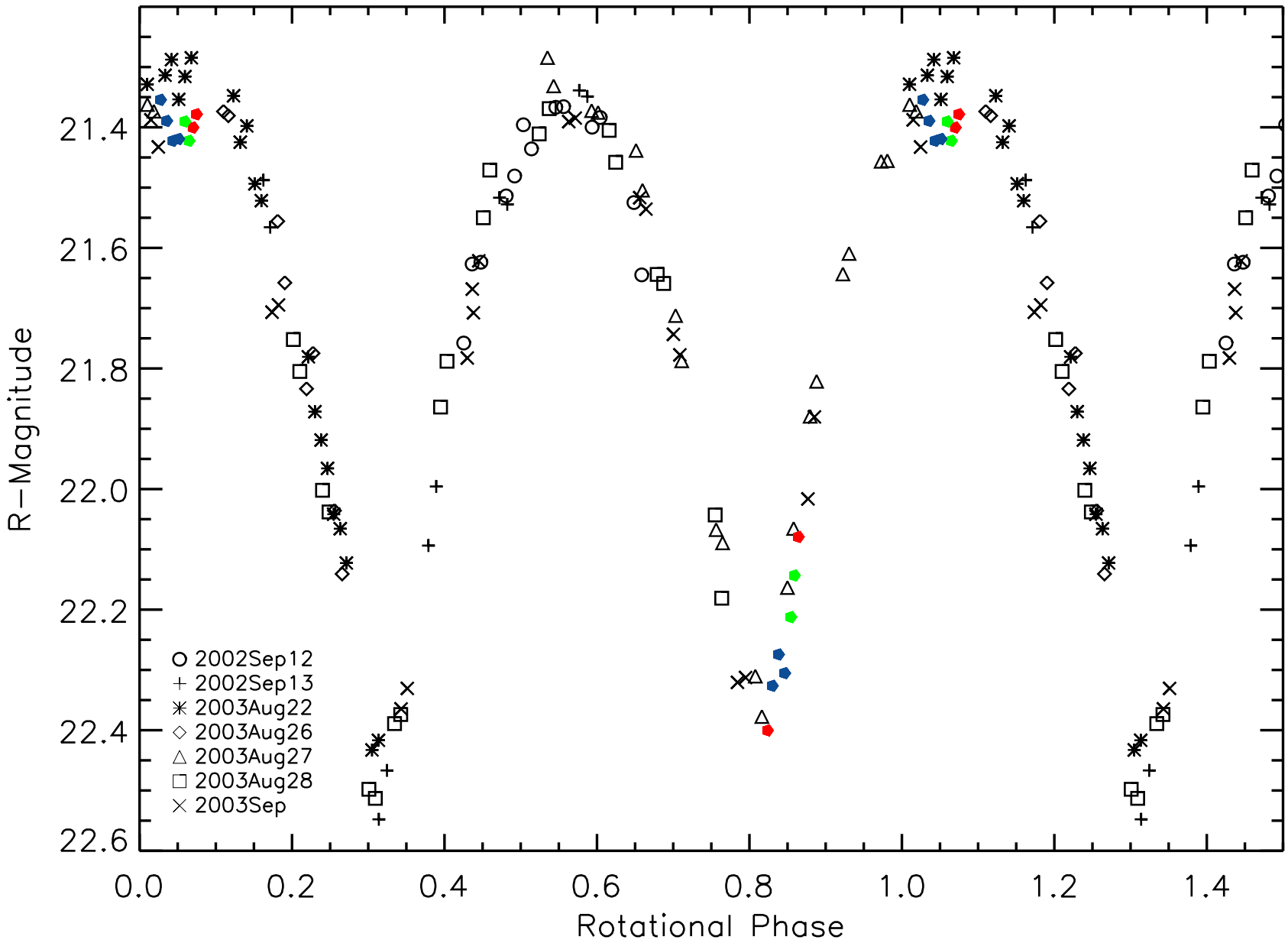
Fig. 4.— A closer view of the phase dispersion minimization (PDM) plot for 2001 $QG_{298}$ around the double-peaked period at 13.7744 hr. The best fit is flanked by aliases from separation of the 3 data sets obtained for this object. Only the center PDM peak fits the data once it is phased together.

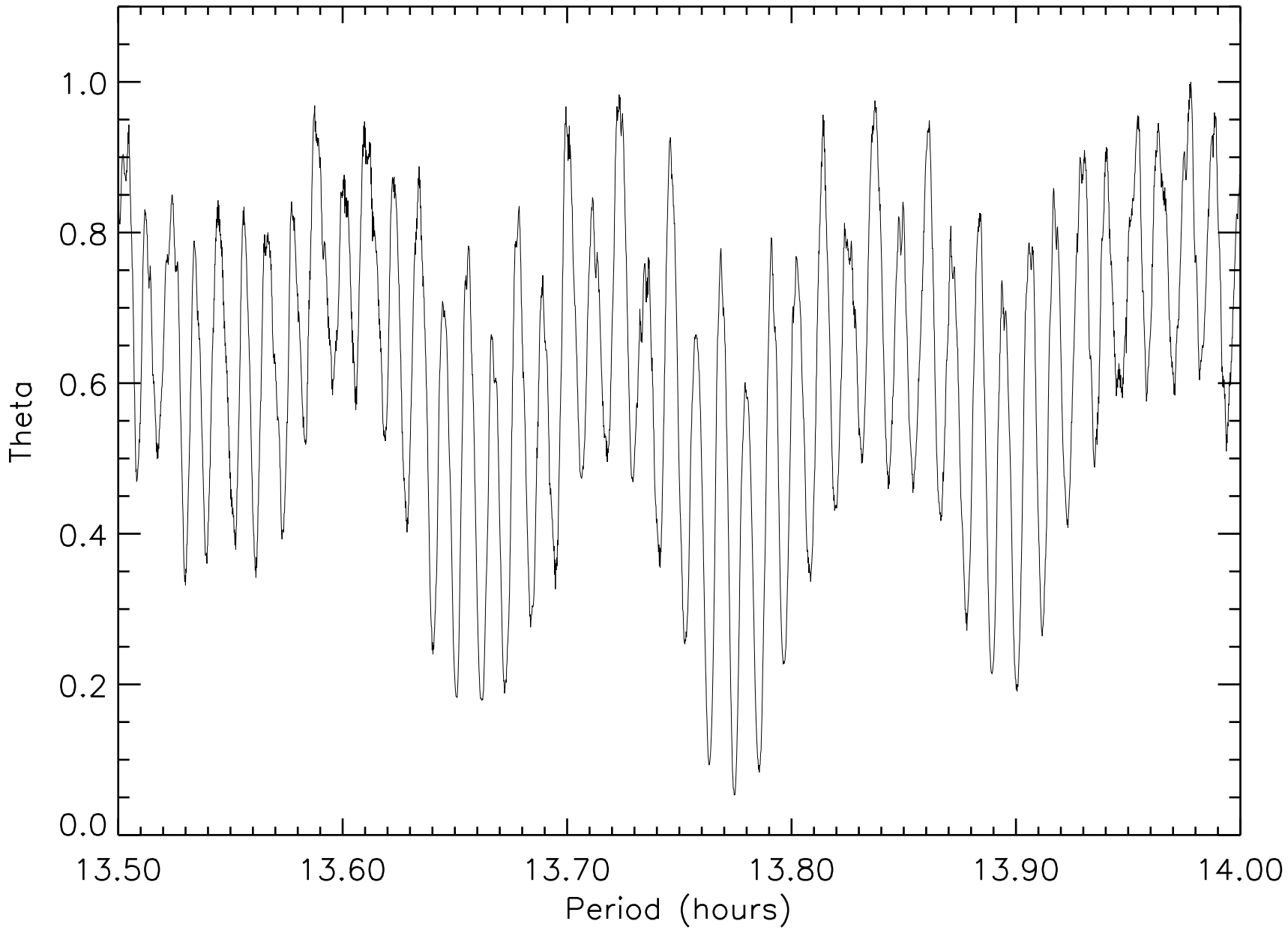
Fig. 5.— This Figure is a modification of Figure 4 from Leone et al. (1984). We here show the rotation periods and photometric ranges of known KBO lightcurves and the larger asteroids. The Regions are defined as A) The range of the lightcurve could be equally caused by albedo, elongation or binarity B) The lightcurve range is most likely caused by rotational elongation C) The lightcurve range is most likely caused by binarity of the object. Stars denote KBOs, Circles denote main-belt asteroids (radii $\geq$ 100 km) and Squares denote the Trojan 624 Hektor and the main-belt asteroid 216 Kleopatra. Objects just to the left of Region B would have densities significantly less than 1000 kg $m^{-3}$ in order to be elongated from rotational angular momentum. Binary objects are not expected to have photometric ranges above 1.2 magnitudes. The 23 KBOs which have photometric ranges below our photometric uncertainties ($\sim$ 0.1 mag) in our Hawaii survey have not been plotted since their periods are unknown. These objects would all fall into Region A. The asteroids have been plotted at their expected mean projected viewing angle of 60 degrees in order to more directly compare to the KBOs of unknown projection angle.

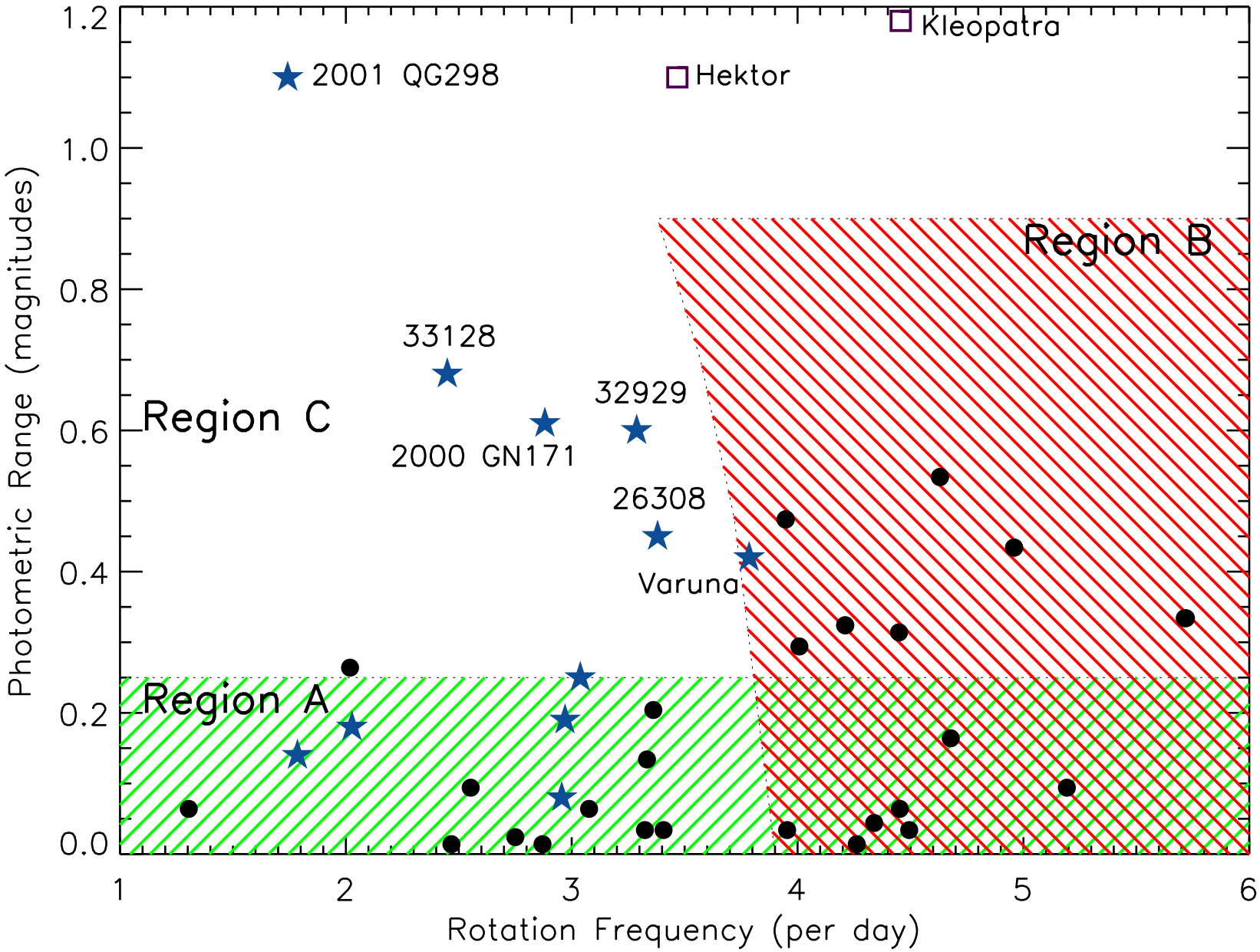
Fig. 6.— A histogram of known KBOs photometric ranges. There is a break in known photometric ranges starting around 0.25 magnitudes. The Regions are defined as 1) The lightcurve range could be dominated by albedo, elongation or binarity 2) The lightcurve is likely dominated from rotational elongation or binarity 3) The lightcurve is likely caused by binarity. Data is from our Hawaii Kuiper Belt object variability project (Sheppard & Jewitt 2002 and Sheppard and Jewitt 2004).


1.0
0.8
0.6
0.4
0.2
0.0
Theta
4
6
8
10
12
14
Period (hours)


R−Magnitude
21.4
21.6
21.8
22.0
22.2
22.4
22.6
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Rotational Phase
2002Sep12
2002Sep13
2003Aug22
2003Aug26
2003Aug27
2003Aug28
2003Sep


R−Magnitude
21.4
21.6
21.8
22.0
22.2
22.4
22.6
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Rotational Phase
2002Sep12
2002Sep13
2003Aug22
2003Aug26
2003Aug27
2003Aug28
2003Sep


1.0
0.8
0.6
0.4
0.2
0.0
Theta
13.50
13.60
13.70
13.80
13.90
14.00
Period (hours)


Kleopatra
2001 QG298
Hektor
Region B
33128
32929
Region C
2000 GN171
26308
Varuna
Region A
Photometric Range (magnitudes)
Rotation Frequency (per day)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1
2
3
4
5
6

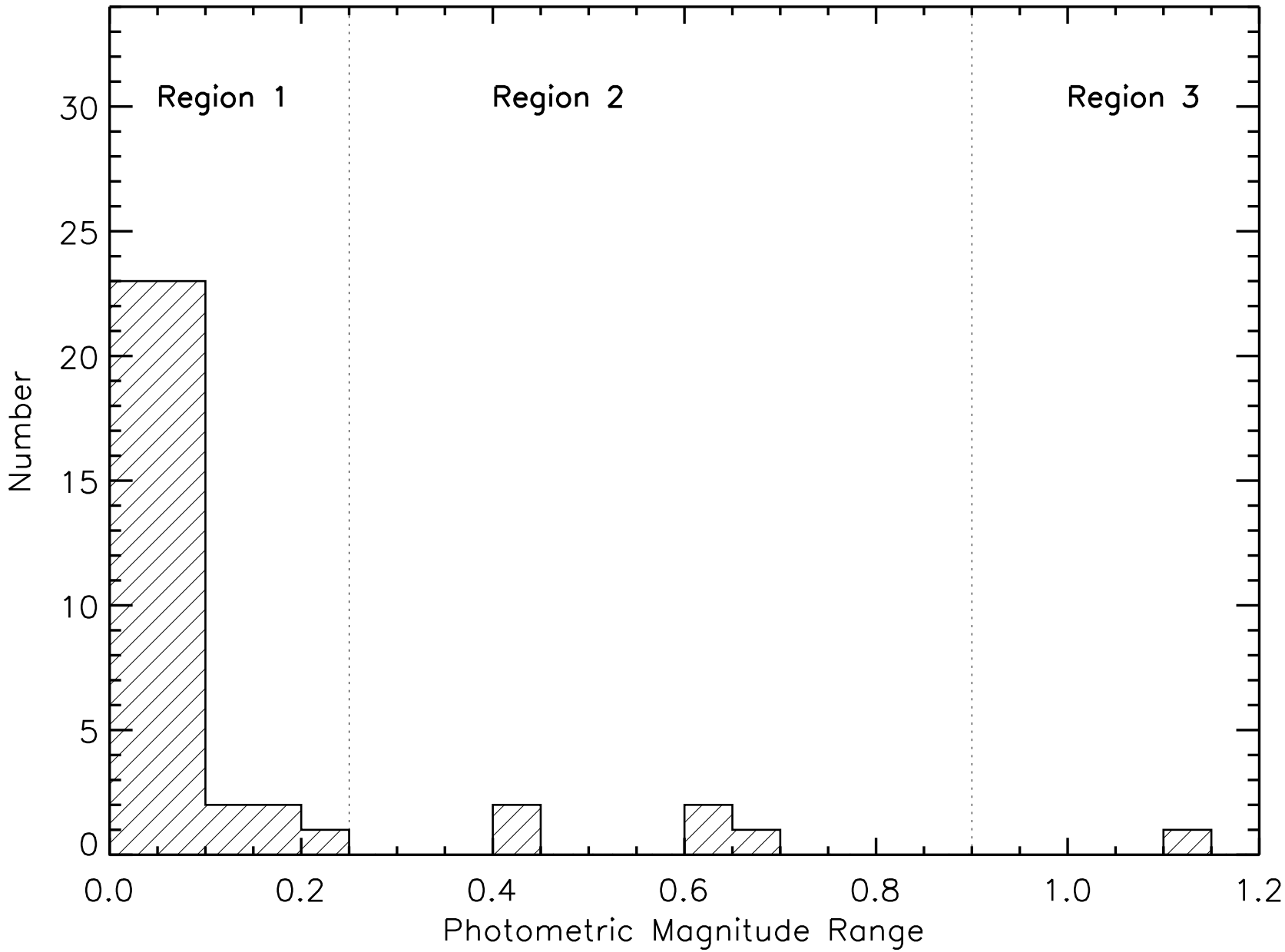

Region 1
Region 2
Region 3
Number
0
5
10
15
20
25
30
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Photometric Magnitude Range

TABLE 1. Geometrical Circumstances of the Observations

| UT Date | R (AU) | $\Delta$ (AU) | $\alpha$ (deg) |
|---|---|---|---|
| 2002 Sep 12 | 32.0028 | 30.9994 | 0.151 |
| 2002 Sep 13 | 32.0026 | 30.9983 | 0.119 |
| 2003 Aug 22 | 31.9392 | 31.0405 | 0.851 |
| 2003 Aug 26 | 31.9385 | 31.0112 | 0.738 |
| 2003 Aug 27 | 31.9384 | 31.0046 | 0.709 |
| 2003 Aug 28 | 31.9382 | 30.9982 | 0.680 |
| 2003 Aug 30 | 31.9378 | 30.9863 | 0.622 |
| 2003 Sep 27 | 31.9330 | 30.9407 | 0.253 |
| 2003 Sep 28 | 31.9328 | 30.9434 | 0.283 |
| 2003 Sep 30 | 31.9325 | 30.9497 | 0.345 |

TABLE 2. R-band Observations at the UH 2.2 meter telescope

| Image[a] | UT Date[b] | Julian Date[c] | Exp[d] (sec) | Mag.[e] ($m_R$) |
|---|---|---|---|---|
| nt3023 | 2002 Sep 12.32535 | 2452529.825347 | 450 | 21.673 |
| nt3024 | 2002 Sep 12.33185 | 2452529.831840 | 450 | 21.542 |
| nt3025 | 2002 Sep 12.33836 | 2452529.838356 | 450 | 21.539 |
| nt3028 | 2002 Sep 12.35733 | 2452529.857326 | 450 | 21.429 |
| nt3029 | 2002 Sep 12.36383 | 2452529.863819 | 450 | 21.396 |
| nt3030 | 2002 Sep 12.37045 | 2452529.870451 | 400 | 21.311 |
| nt3031 | 2002 Sep 12.37646 | 2452529.876458 | 400 | 21.351 |
| nt3034 | 2002 Sep 12.39474 | 2452529.894734 | 400 | 21.282 |
| nt3035 | 2002 Sep 12.40065 | 2452529.900648 | 400 | 21.281 |
| nt3038 | 2002 Sep 12.42219 | 2452529.922188 | 400 | 21.315 |
| nt3039 | 2002 Sep 12.42811 | 2452529.928102 | 400 | 21.299 |
| nt3043 | 2002 Sep 12.45360 | 2452529.953600 | 400 | 21.440 |
| nt3044 | 2002 Sep 12.45952 | 2452529.959514 | 400 | 21.560 |
| nt4047 | 2002 Sep 13.32242 | 2452530.822419 | 350 | 21.398 |
| nt4048 | 2002 Sep 13.32776 | 2452530.827755 | 350 | 21.476 |
| nt4071 | 2002 Sep 13.40951 | 2452530.909514 | 400 | 22.458 |
| nt4072 | 2002 Sep 13.41544 | 2452530.915428 | 400 | 22.377 |
| nt4083 | 2002 Sep 13.44672 | 2452530.946725 | 400 | 22.004 |
| nt4084 | 2002 Sep 13.45264 | 2452530.952639 | 400 | 21.906 |
| nt4097 | 2002 Sep 13.50026 | 2452531.000255 | 400 | 21.427 |
| nt4098 | 2002 Sep 13.50617 | 2452531.006169 | 400 | 21.438 |
| nt4112 | 2002 Sep 13.56040 | 2452531.060394 | 400 | 21.249 |
| nt4113 | 2002 Sep 13.56631 | 2452531.066308 | 400 | 21.259 |
| f.114 | 2003 Aug 22.44983 | 2452873.949815 | 400 | 21.356 |
| f.115 | 2003 Aug 22.46309 | 2452873.963079 | 400 | 21.341 |
| f.116 | 2003 Aug 22.46815 | 2452873.968125 | 400 | 21.315 |
| f.117 | 2003 Aug 22.47331 | 2452873.973287 | 380 | 21.381 |
| f.118 | 2003 Aug 22.47812 | 2452873.978090 | 380 | 21.343 |
| f.119 | 2003 Aug 22.48288 | 2452873.982859 | 380 | 21.312 |
| f.124 | 2003 Aug 22.51473 | 2452874.014711 | 380 | 21.375 |
| f.125 | 2003 Aug 22.51984 | 2452874.019815 | 380 | 21.452 |
| f.126 | 2003 Aug 22.52467 | 2452874.024630 | 380 | 21.425 |
| f.127 | 2003 Aug 22.53082 | 2452874.030799 | 380 | 21.521 |
| f.128 | 2003 Aug 22.53559 | 2452874.035567 | 380 | 21.549 |
| f.138 | 2003 Aug 22.57113 | 2452874.071111 | 380 | 21.808 |
| f.139 | 2003 Aug 22.57589 | 2452874.075868 | 380 | 21.899 |
| f.140 | 2003 Aug 22.58063 | 2452874.080613 | 380 | 21.946 |
| f.141 | 2003 Aug 22.58543 | 2452874.085405 | 380 | 21.993 |
| f.142 | 2003 Aug 22.59016 | 2452874.090150 | 380 | 22.069 |
| f.143 | 2003 Aug 22.59494 | 2452874.094919 | 380 | 22.093 |
| f.144 | 2003 Aug 22.59972 | 2452874.099699 | 380 | 22.150 |
| f.147 | 2003 Aug 22.61900 | 2452874.118981 | 380 | 22.460 |
| f.148 | 2003 Aug 22.62375 | 2452874.123738 | 380 | 22.444 |
| nt1115 | 2003 Aug 26.52466 | 2452878.024653 | 300 | 21.383 |
| nt1116 | 2003 Aug 26.52830 | 2452878.028287 | 300 | 21.390 |
| nt1137 | 2003 Aug 26.56556 | 2452878.065544 | 400 | 21.565 |
| nt1138 | 2003 Aug 26.57085 | 2452878.070833 | 400 | 21.667 |
| nt1141 | 2003 Aug 26.58721 | 2452878.087187 | 400 | 21.843 |

TABLE 2. (continued)

| Image[a] | UT Date[b] | Julian Date[c] | Exp[d] (sec) | Mag.[e] ($m_R$) |
|---|---|---|---|---|
| nt1142 | 2003 Aug 26.59203 | 2452878.092014 | 400 | 21.784 |
| nt1145 | 2003 Aug 26.60817 | 2452878.108171 | 400 | 22.045 |
| nt1146 | 2003 Aug 26.61414 | 2452878.114120 | 400 | 22.150 |
| nt2057 | 2003 Aug 27.34245 | 2452878.842442 | 400 | 21.289 |
| nt2058 | 2003 Aug 27.34729 | 2452878.847280 | 400 | 21.336 |
| nt2068 | 2003 Aug 27.37572 | 2452878.875706 | 400 | 21.377 |
| nt2069 | 2003 Aug 27.38053 | 2452878.880521 | 400 | 21.380 |
| nt2072 | 2003 Aug 27.40915 | 2452878.909144 | 400 | 21.443 |
| nt2073 | 2003 Aug 27.41403 | 2452878.914016 | 400 | 21.509 |
| nt2080 | 2003 Aug 27.43887 | 2452878.938854 | 400 | 21.717 |
| nt2081 | 2003 Aug 27.44368 | 2452878.943669 | 400 | 21.792 |
| nt2090 | 2003 Aug 27.46950 | 2452878.969479 | 400 | 22.072 |
| nt2091 | 2003 Aug 27.47431 | 2452878.974294 | 400 | 22.094 |
| nt2098 | 2003 Aug 27.49900 | 2452878.998981 | 400 | 22.315 |
| nt2099 | 2003 Aug 27.50382 | 2452879.003808 | 400 | 22.382 |
| nt2104 | 2003 Aug 27.52311 | 2452879.023090 | 400 | 22.168 |
| nt2105 | 2003 Aug 27.52795 | 2452879.027928 | 400 | 22.070 |
| nt2108 | 2003 Aug 27.54033 | 2452879.040324 | 400 | 21.884 |
| nt2109 | 2003 Aug 27.54516 | 2452879.045139 | 400 | 21.826 |
| nt2114 | 2003 Aug 27.56485 | 2452879.064826 | 400 | 21.648 |
| nt2115 | 2003 Aug 27.56971 | 2452879.069688 | 400 | 21.614 |
| nt2122 | 2003 Aug 27.59367 | 2452879.093657 | 400 | 21.461 |
| nt2123 | 2003 Aug 27.59849 | 2452879.098472 | 400 | 21.460 |
| nt2127 | 2003 Aug 27.61524 | 2452879.115220 | 400 | 21.367 |
| nt2128 | 2003 Aug 27.62006 | 2452879.120046 | 400 | 21.378 |
| nt3062 | 2003 Aug 28.29908 | 2452879.799074 | 400 | 21.752 |
| nt3063 | 2003 Aug 28.30389 | 2452879.803877 | 400 | 21.805 |
| nt3066 | 2003 Aug 28.32106 | 2452879.821053 | 400 | 22.002 |
| nt3067 | 2003 Aug 28.32587 | 2452879.825868 | 400 | 22.038 |
| nt3079 | 2003 Aug 28.35605 | 2452879.856042 | 400 | 22.498 |
| nt3080 | 2003 Aug 28.36082 | 2452879.860810 | 400 | 22.513 |
| nt3083 | 2003 Aug 28.37516 | 2452879.875150 | 400 | 22.389 |
| nt3084 | 2003 Aug 28.37992 | 2452879.879907 | 400 | 22.374 |
| nt3093 | 2003 Aug 28.40996 | 2452879.909942 | 400 | 21.864 |
| nt3094 | 2003 Aug 28.41477 | 2452879.914757 | 400 | 21.788 |
| nt3108 | 2003 Aug 28.44225 | 2452879.942234 | 400 | 21.550 |
| nt3109 | 2003 Aug 28.44701 | 2452879.946991 | 400 | 21.471 |
| nt3132 | 2003 Aug 28.48418 | 2452879.984167 | 400 | 21.411 |
| nt3133 | 2003 Aug 28.49170 | 2452879.991690 | 400 | 21.369 |
| nt3164 | 2003 Aug 28.53695 | 2452880.036933 | 400 | 21.405 |
| nt3165 | 2003 Aug 28.54172 | 2452880.041713 | 400 | 21.458 |
| nt3187 | 2003 Aug 28.57313 | 2452880.073113 | 400 | 21.644 |
| nt3188 | 2003 Aug 28.57790 | 2452880.077882 | 400 | 21.659 |
| nt3215 | 2003 Aug 28.61676 | 2452880.116748 | 400 | 22.043 |
| nt3216 | 2003 Aug 28.62153 | 2452880.121516 | 400 | 22.181 |
| nt1.034 | 2003 Aug 27.27855 | 2452909.778553 | 300 | 21.600 |
| nt1.035 | 2003 Aug 27.28337 | 2452909.783368 | 300 | 21.553 |
| nt1.067 | 2003 Aug 27.42997 | 2452909.929965 | 300 | 21.675 |

TABLE 2. (continued)

| Image[a] | UT Date[b] | Julian Date[c] | Exp[d] (sec) | Mag.[e] ($m_R$) |
|---|---|---|---|---|
| nt1.068 | 2003 Aug 27.43473 | 2452909.934734 | 300 | 21.709 |
| nt1.089 | 2003 Aug 27.53125 | 2452910.031238 | 300 | 21.948 |
| nt1.090 | 2003 Aug 27.53605 | 2452910.036042 | 300 | 21.812 |
| nt2.032 | 2003 Aug 28.27564 | 2452910.775637 | 300 | 21.643 |
| nt2.033 | 2003 Aug 28.28043 | 2452910.780428 | 300 | 21.631 |
| nt2.053 | 2003 Aug 28.37271 | 2452910.872708 | 300 | 22.301 |
| nt2.054 | 2003 Aug 28.37751 | 2452910.877512 | 300 | 22.267 |
| nt2.063 | 2003 Aug 28.42250 | 2452910.922500 | 300 | 21.719 |
| nt2.064 | 2003 Aug 28.42730 | 2452910.927292 | 300 | 21.644 |
| nt2.080 | 2003 Aug 28.49909 | 2452910.999086 | 300 | 21.327 |
| nt2.081 | 2003 Aug 28.50389 | 2452911.003889 | 300 | 21.321 |
| nt2.090 | 2003 Aug 28.55245 | 2452911.052442 | 300 | 21.453 |
| nt2.091 | 2003 Aug 28.55725 | 2452911.057245 | 300 | 21.472 |
| nt2.166 | 2003 Aug 30.34785 | 2452912.847847 | 400 | 22.267 |
| nt2.167 | 2003 Aug 30.35398 | 2452912.853981 | 400 | 22.259 |
| nt2.195 | 2003 Aug 30.48012 | 2452912.980116 | 400 | 21.334 |
| nt2.196 | 2003 Aug 30.48597 | 2452912.985961 | 400 | 21.379 |

[a]Image number.
[b]Decimal Universal Date at the start of the integration.
[c]Julian Date at the start of the integration. No light-time correction has been made in the table.
[d]Exposure time for the image.
[e]Apparent red magnitude, uncertainties are $\pm 0.03$ to $\pm 0.04$.

TABLE 3. B-band, V-band and R-band Observations at Keck

| Image[a] | UT Date[b] | Julian Date[c] | Exp[d] (sec) | Mag. |
|---|---|---|---|---|
| lred0078 | 2003 Aug 30.37786 | 2452881.877861 | 150 | 22.391[e] |
| lred0084 | 2003 Aug 30.40107 | 2452881.901076 | 150 | 22.070[e] |
| lred0120 | 2003 Aug 30.51921 | 2452882.019213 | 150 | 21.391[e] |
| lred0121 | 2003 Aug 30.52202 | 2452882.022027 | 150 | 21.369[e] |
| lred0082 | 2003 Aug 30.39546 | 2452881.895460 | 150 | 22.803[f] |
| lred0083 | 2003 Aug 30.39828 | 2452881.898285 | 150 | 22.734[f] |
| lred0118 | 2003 Aug 30.51329 | 2452882.013295 | 150 | 21.981[f] |
| lred0119 | 2003 Aug 30.51642 | 2452882.016423 | 150 | 22.013[f] |
| lred0079 | 2003 Aug 30.38170 | 2452881.881700 | 300 | 23.917[g] |
| lred0080 | 2003 Aug 30.38623 | 2452881.886232 | 300 | 23.865[g] |
| lred0081 | 2003 Aug 30.39075 | 2452881.890758 | 300 | 23.896[g] |
| lred0114 | 2003 Aug 30.49488 | 2452881.994882 | 300 | 22.945[g] |
| lred0115 | 2003 Aug 30.49949 | 2452881.999492 | 300 | 22.980[g] |
| lred0116 | 2003 Aug 30.50404 | 2452882.004046 | 300 | 23.013[g] |
| lred0117 | 2003 Aug 30.50860 | 2452882.008606 | 300 | 23.010[g] |

[a]Image number.

[b]Decimal Universal Date at the start of the integration.

[c]Julian Date at the start of the integration. No light-time correction has been made in the table.

[d]Exposure time for the image.

[e]Apparent red magnitude, uncertainties are $\pm 0.02$.

[f]The apparent magnitude is for the V-band, uncertainties are $\pm 0.03$

[g]The apparent magnitude is for the B-band, uncertainties are $\pm 0.04$. In the B-band, only light longward of 0.460 $\mu$m was observed because of the dichroic.

TABLE 4. Large Objects With Extreme Light Curves[a]

| Name | Type | $a \times b$ (km) | $\Delta$ mag (mag) | Period (hrs) | Cause[b] | Ref[c] |
|---|---|---|---|---|---|---|
| Iapetus | Saturn Satellite | $715 \times 715$ | 2 | 1903.9 | AL | 1 |
| 624 Hektor | Jupiter Trojan | $150 \times 75$ | 1.1 | 6.921 | CB | 2 |
| 216 Kleopatra | Main-Belt Asteroid | $109 \times 47$ | 1.18 | 5.385 | JE/CB | 3 |
| 2001 $QG_{298}$ | Kuiper Belt Object | $267 \times 94$ | 1.14 | 13.7744 | CB | This Work |

[a]Objects that have effective radii $> 25$ km and lightcurves with peak-to-peak amplitudes $> 1$ magnitudes.

[b]The dominant cause or most probable dominant cause for the amplitude of the lightcurve: AL is albedo, CB is contact binary, JE is Jacobi triaxial rotational ellipsoid

[c]References for specified objects: 1) Millis (1977) 2) Dunlap & Gehrels (1969); Hartmann & Cruikshank (1978); Weidenschilling (1980); Leone et al. (1984); Lagerkvist, Harris & Zappala (1989) 3) Scaltriti & Zappala (1978); Tholen (1980); Leone et al. (1984); Lagerkvist, Harris & Zappala (1989); Ostro et al. (2000); Hestroffer et al. (2002); Washabaugh & Scheeres (2002)

TABLE 5. Possible Contact Binaries in the Kuiper Belt

| Name | | $H$[a] (mag) | $\Delta m_R$[b] (mag) | Period[c] (hrs) | Probability[d] | Ref[e] |
|---|---|---|---|---|---|---|
| | 2001 $QG_{298}$ | 6.85 | $1.14 \pm 0.04$ | $13.7744 \pm 0.0004$ | very high | This Work |
| | 2000 $GN_{171}$ | 5.98 | $0.61 \pm 0.03$ | $8.329 \pm 0.005$ | high | 1 |
| (33128) | 1998 $BU_{48}$ | 7.2 | $0.68 \pm 0.04$ | $9.8 \pm 0.1$ | high | 1 |
| (26308) | 1998 $SM_{165}$ | 5.8 | $0.45 \pm 0.03$ | $7.1 \pm 0.1$ | medium | 1,2 |
| (32929) | 1995 $QY_9$ | 7.5 | $0.60 \pm 0.04$ | $7.3 \pm 0.1$ | medium | 1 |
| (20000) Varuna | 2000 $WR_{106}$ | 3.21 | $0.42 \pm 0.03$ | $6.34 \pm 0.01$ | low | 3 |

[a]Absolute magnitude.

[b]The peak to peak range of the lightcurve.

[c]The lightcurve period if there is two maximum per period.

[d]Probability that the object is a contact or nearly contact binary.

[e]References for lightcurve information: 1) Sheppard & Jewitt (2002) 2) Romanishin et al. (2001) 3) Jewitt & Sheppard (2002)